

National Aeronautics and Space Administration



**NDL**

**NAVIGATION DOPPLER LIDAR**

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**AIAA Hampton Roads Section Technical Seminar**

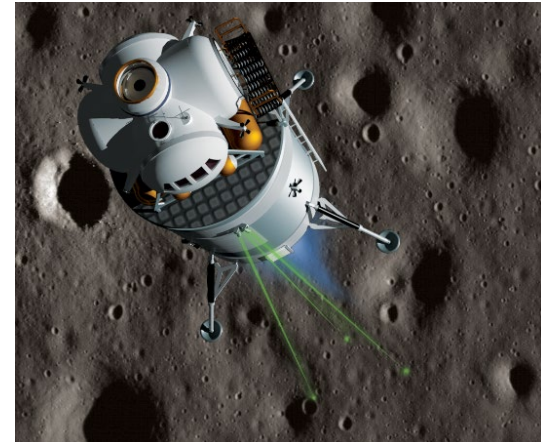
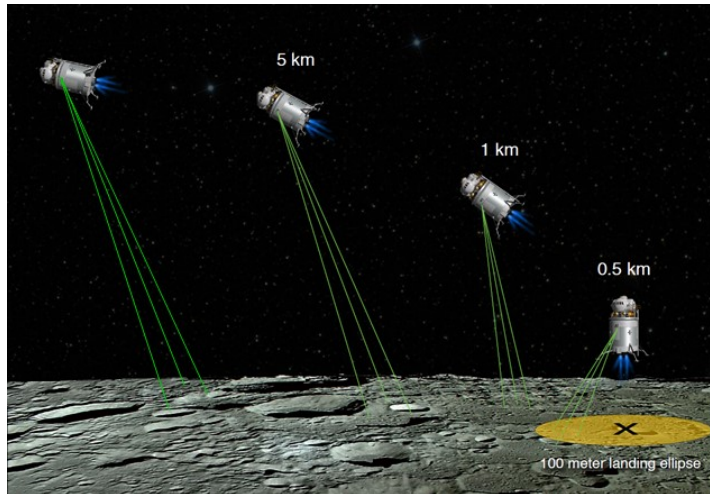
**April 1, 2022**



# Navigation Doppler Lidar (NDL)



- NDL is a laser sensor capable of providing precision vector velocity and altitude data
- Viable replacement for radars with an order of magnitude higher precision and much better data quality
  - Enables “*precision navigation*” to the designated landing location
  - Enables “*well-controlled*” descent, landing, and ascent maneuvers to within a few cm/sec

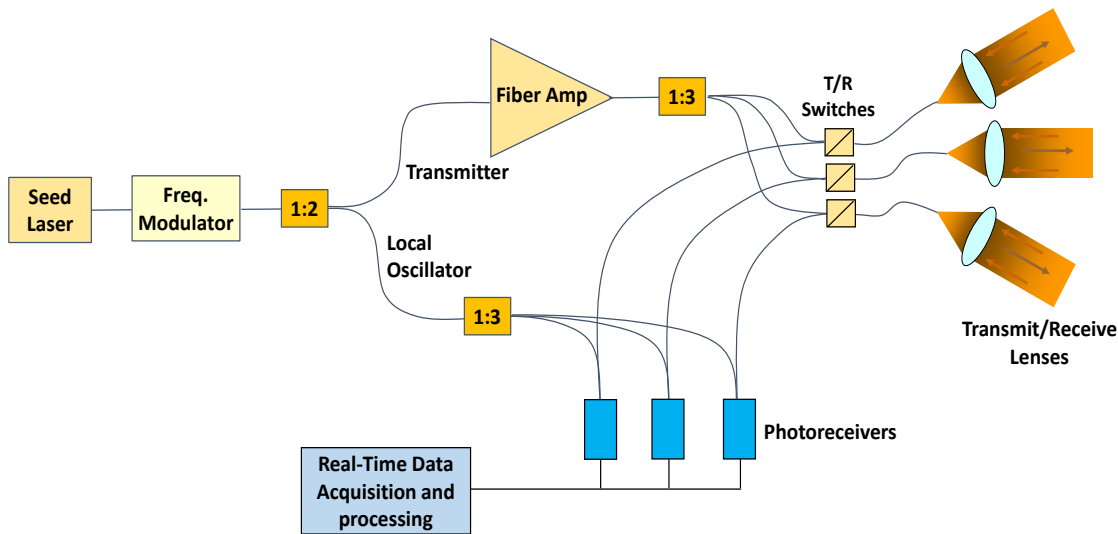




# Navigation Doppler Lidar (NDL)



- Utilizes FMCW technique to measure velocity and range along three laser beams
- Simultaneous line-of-sight measurements are used to estimate:
  - Velocity Vector ( $V$ )
  - Altitude relative to local ground (No external data required)





# NDL from Concept to Lunar Landing Demonstration



2008

Breadboard without real-time processing

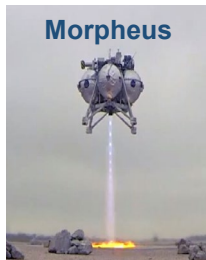
Proof-of-Concept



2010



2012



Morpheus

2014



Masten

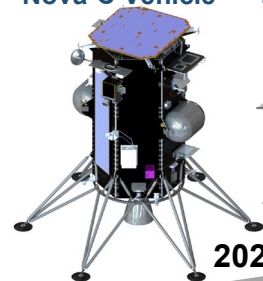
2017



New Shepard

2021

Intuitive Machines  
Nova-C Vehicle



Astrobotic  
Peregrine Vehicle



2022

Spaceflight ETU

Fully-Autonomous Prototype

GEN 1



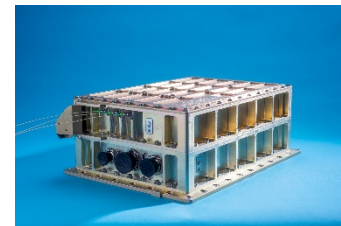
GEN 2



GEN 3



GEN 4



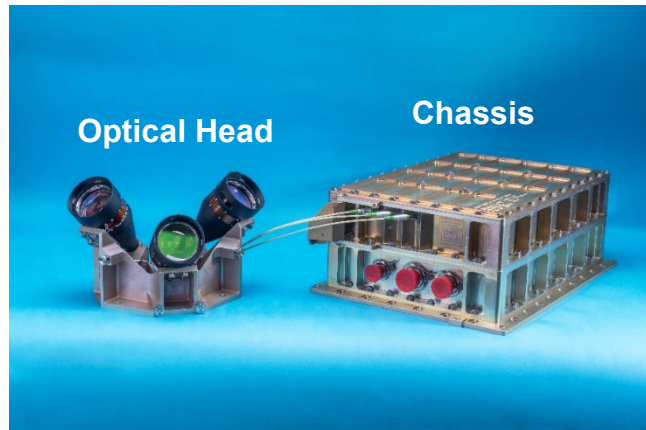


# Spaceflight Engineering Test Units (ETUs)



## 4 ETUs have been built and tested

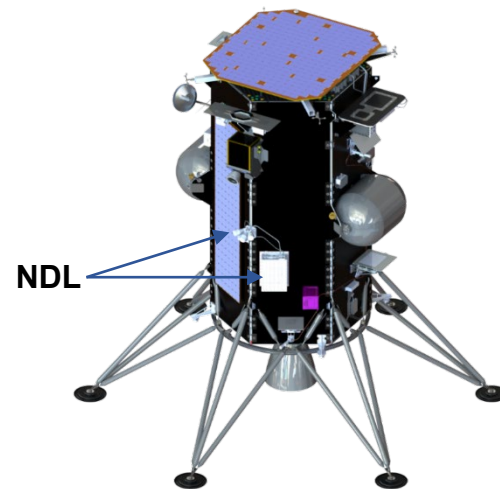
- # 1 – Aircraft flight tests and integrated tests with other avionics
- # 2 – Suborbital flight test on Blue Origin New Shepard vehicle (2021)
- # 3 – Lunar Landing Demonstration onboard Intuitive Machines lander (2022)
- # 4 – Lunar Landing Demonstration onboard Astrobotic lander (2022)



Astrobotic  
Peregrine Vehicle



Intuitive Machines  
Nova-C Vehicle

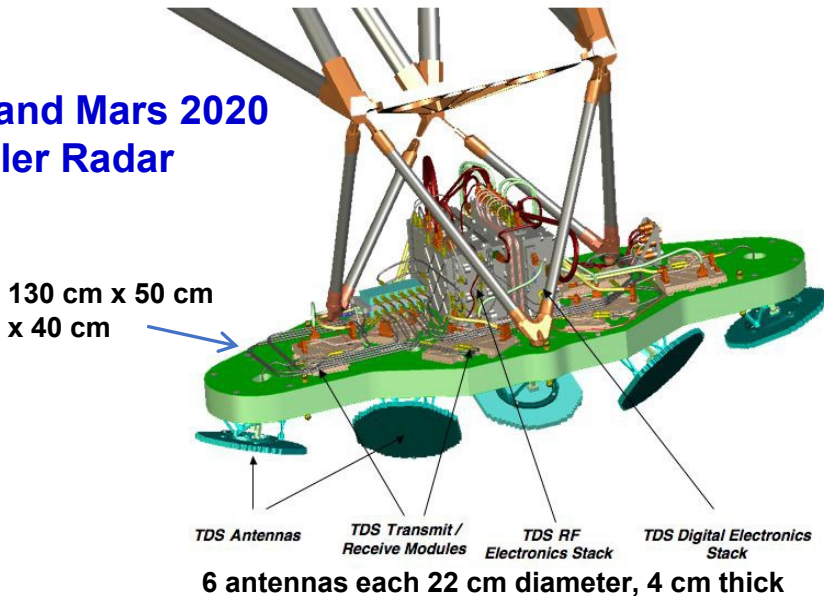




# Comparison of NDL and Mars Landing Radar



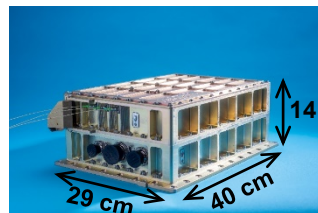
## MSL and Mars 2020 Doppler Radar



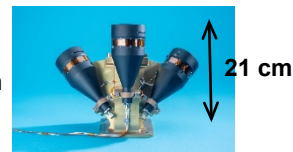
- > 10X higher precision
- 3 orders of magnitude tighter beams
- 40% reduction in power, 50% in mass, and 60% in size

## NDL ETU

Chassis



Optical Head

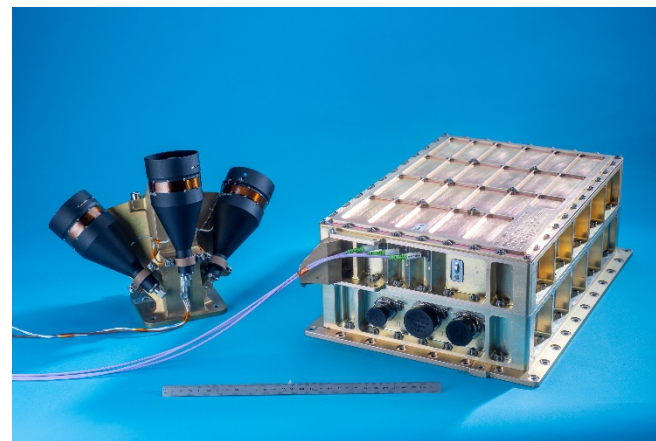


	MSL and Mars 2020 Radar	NDL ETU
Mass (kg)	26	15
Power (W)	125	78

## Not Including Vehicle Effects

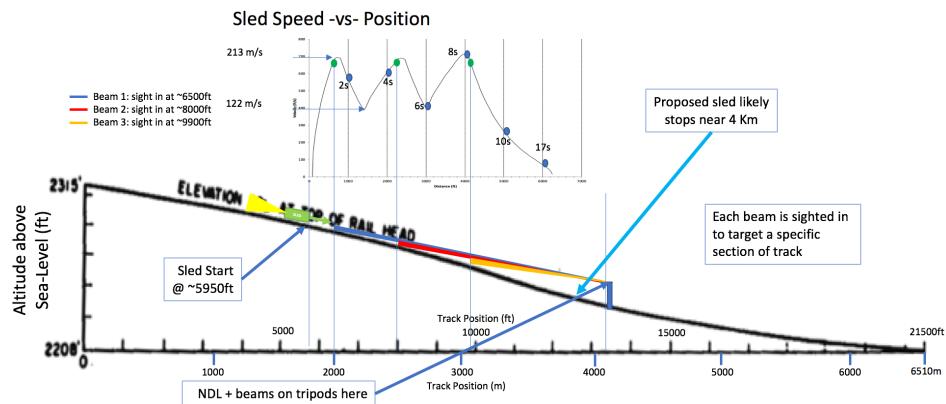
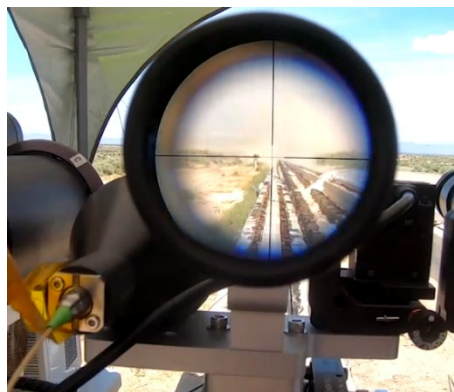
Maximum LOS Range <sup>1,2</sup>		> 10 km
Maximum LOS Velocity		+/- 218 m/sec
LOS Velocity Error <sup>2</sup>		0.2 cm/sec
LOS Range Error <sup>2</sup>		12.5 cm
Data Rate		20 Hz
Dimensions	Electronic Chassis	15.6" x 11.3" x 5.7"
	Optical Head	10.8" x 8.5" x 4.9"
Mass	Electronic Chassis	13.0 kg
	Optical Head	2.2 kg
Power (28 VDC)		78 W

1. Dependent on atmosphere and surface albedo
2. Vehicle dynamics degrades maximum range and measurements precision





# Maximum Velocity Measurement (Rocket-Sled Test)





# *High-Speed Rocket Sled Test*



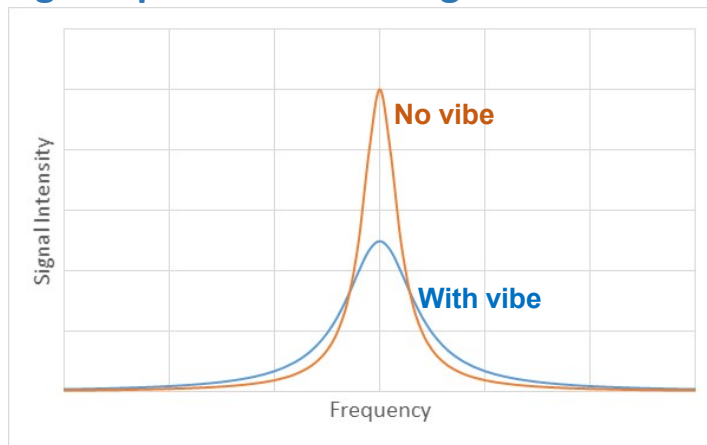


# ***ETU Max Range and Precision are dominated by vehicle vibration***



- **Vibration broadens laser linewidth which in turn broadens the signal frequency spectra and lowers its peak intensity**
  - Reduces maximum operational range
  - Increases measurement noise
- **Signal frequency broadening is proportional to vibration load and increases with range**

**Signal spectra broadening with vibration**





# Comprehensive Functional Test



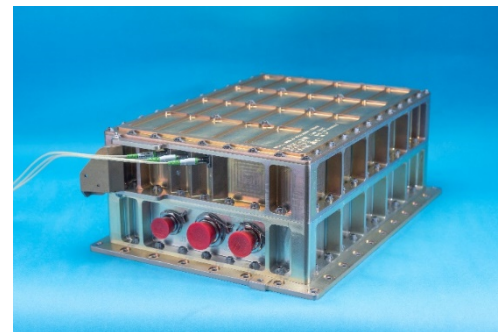
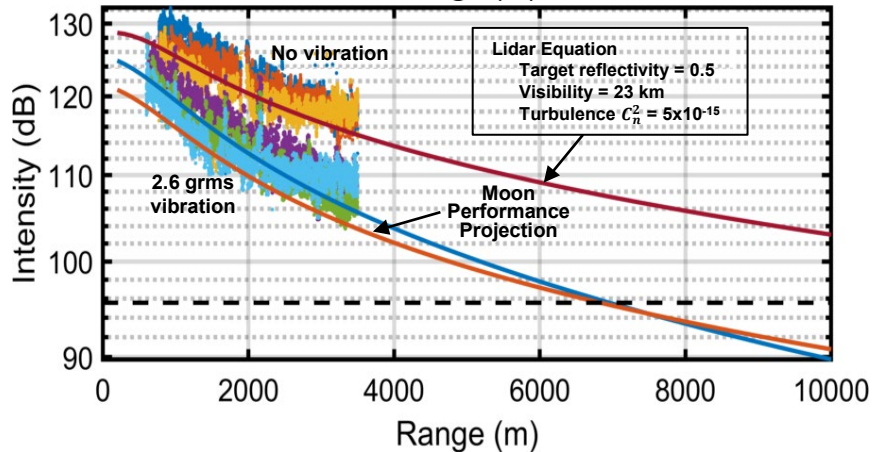
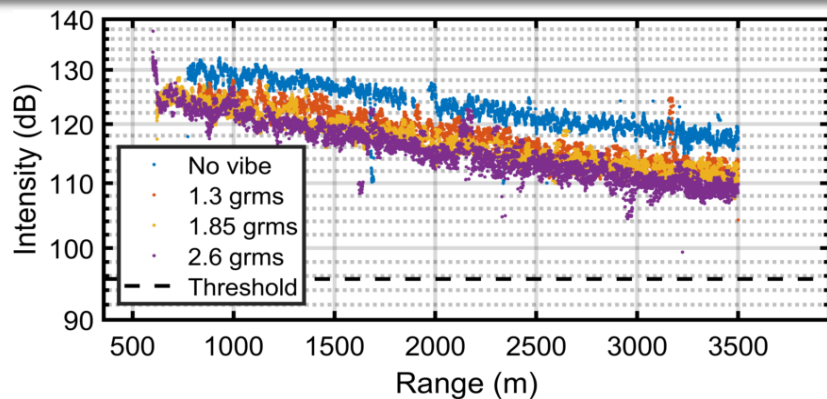
- Measured signal strength and spectral broadening at different vibration loads versus range

## Truck test at Joint Base Langley-Eustis





# Maximum Operational Range



➤ **Maximum operational range in Moon environment is extrapolated from measured data**

- Remove atmospheric effects
- Correct for lunar surface albedo



# Measurements Precision

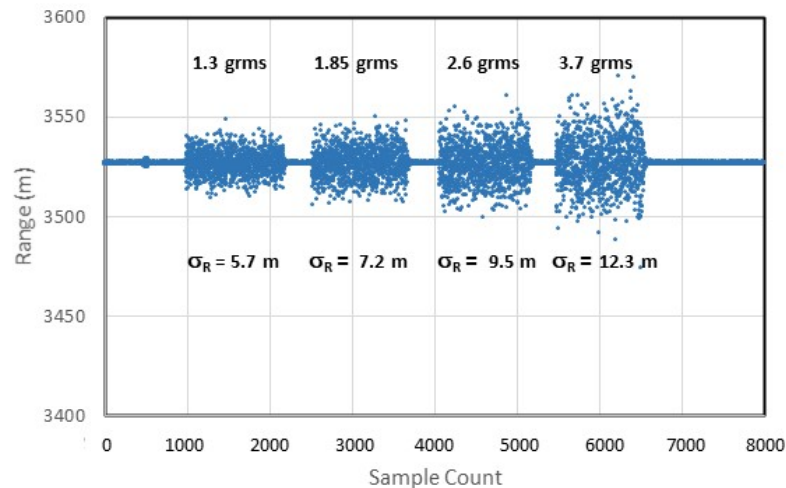


## ➤ Estimated ETU range and velocity precision in 2.6 grms vibration environment:

$$\partial R = 1.59 + 2.21 \times 10^{-3} \times R \text{ m}$$

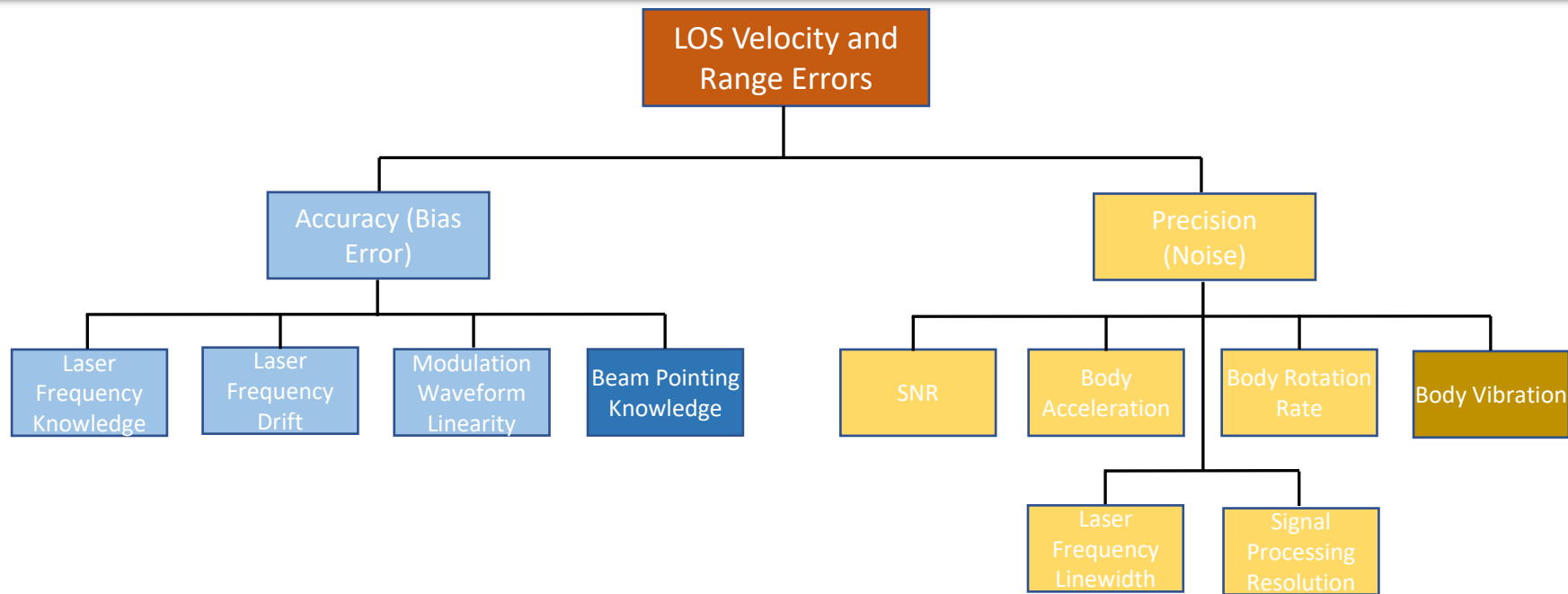
$$\partial v_r = 1.62 \times 10^{-2} + 2.24 \times 10^{-5} \times R \text{ m/s}$$

LOS Range	Range Noise	Velocity Noise
1000 m	3.80 m	3.86 cm/s
6000 m	14.85 m	15.06 cm/s





# NDL Error Budget



- Dominant bias error source is beam pointing knowledge
- Dominant noise source is vehicle vibration



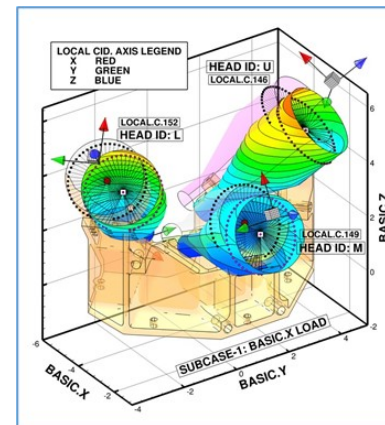
# Beam Pointing Knowledge Error



## ➤ Major sources of beam pointing knowledge error:

- Beam pointing registration error
- Thermal expansion of Optical Head
- Telescope displacement due to launch loads
- Vehicle flexing and thermal effects

## ➤ Performed full Structural, Thermal, Optical, Performance (STOP) analysis





# Measurement Errors Due to Beam Pointing Knowledge Error



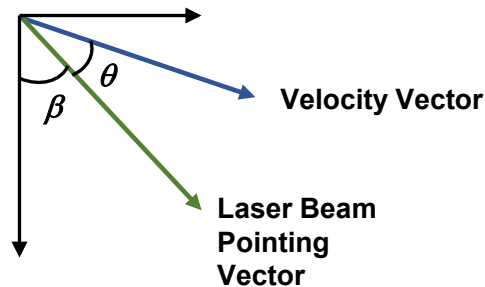
- $\partial v_r = |V| \sin \theta \partial \theta$ 
  - where  $\theta$  is angle between beam vector and velocity vector
- $\partial R_r = |Alt| \sin \beta \partial \beta$ 
  - where  $\beta$  is the angle between the beam vector and normal to the ground

$$\partial v_r = |436| \sin(60^\circ) 0.35 \times 10^{-3}$$

$$\partial v_r = 0.13 \text{ m/s}$$

$$\partial R_r = |6000| \sin(40^\circ) 0.35 \times 10^{-3}$$

$$\partial R_r = 1.34 \text{ m}$$





# ETU Specifications



- **Projected ETU performance for 2022 lunar landing missions including effects of vehicle dynamics:**

Parameter	Value
Maximum LOS Range	6.0 km
Minimum LOS Velocity	+/- 0.1 m/s
Maximum LOS Velocity	+/- 218 m/s
Data Rate	20 Hz
LOS Velocity Error (1- $\sigma$ ) @ 6 km and Max Velocity	0.15 m/s (noise) + 0.13 m/s (bias)
LOS Range Error (1- $\sigma$ ) @ 6 km	14.8 m (noise) + 1.3 m (bias)



# ***Non-Space Applications***



- **Aircraft navigation in GPS-deprived environment**
- **Assist helicopter landing in brownout conditions**
- **Autonomous ground and air vehicles**
- **Exploration of valuable resources on Earth and in space (oil, natural gas, metals, water, etc.)**



**Commercialization is well underway by  
Licensee for both space and non-space markets**



# ***Concluding Remarks***



- **NDL provides critical vehicle velocity and altitude data for precision soft landing on the Moon, Mars, and other solar system bodies**
- **NDL will be demonstrated on two lunar landing vehicles in late 2022**
  - **NDL data will be used by vehicle GN&C system during descent and landing**
- **Performance of the NDL is dominated by the vehicle vibration and thermal environments**
  - **Vehicle vibration impacts maximum operational range and measurement precision**
  - **Thermal and vibration environments impacts measurement bias error**
- **Conducted a series of tests and analyses to estimate the NDL performance for Moon and Mars landing**
- **Technology advancement is underway to reduce mass to 1/3 and power to 1/2 while reducing effects of vehicle vibration**



**Backup**

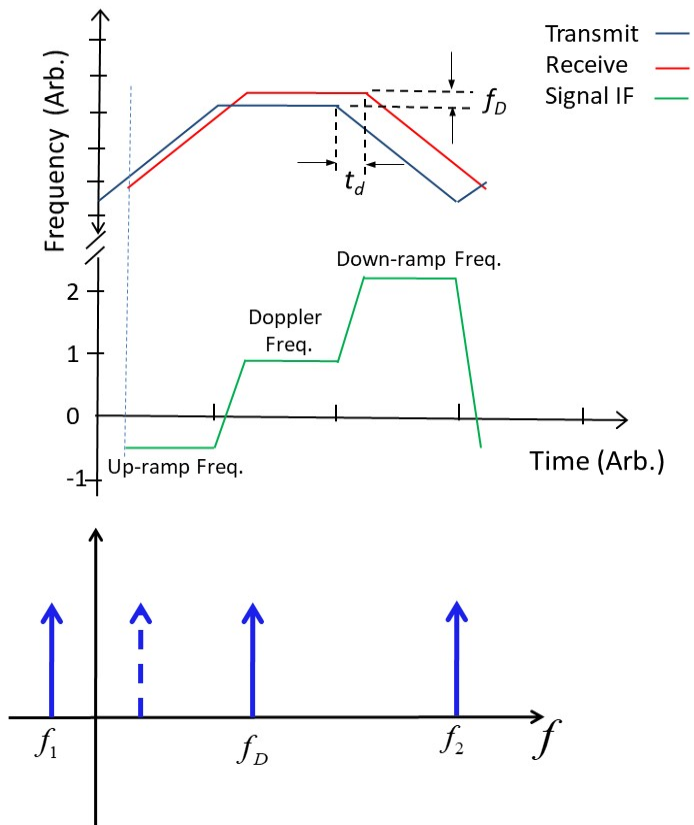


# ***Technology Advancement for Next Generation NDL***

- **Ongoing technology advancement efforts can drastically reduce size, mass, and power, expand its capabilities, and enhance its robustness**
- **Spacecraft landing and aircraft applications**
  - **Thin film Non-Mechanical Beam Steering (NMBS) reduces mass by 40%, power by 20% (ready for infusion in 2023)**
  - **Photonic Integrated Circuit (PIC) reduces mass by 30%, power by 10% (ready for infusion in 2024)**
- **PIC can enable miniature and low-cost NDL for short range autonomous ground vehicles**

# Ambiguity Removal

- **Novel Ambiguity Removal algorithm utilizes 3 segments waveform to minimize:**
- False alarms due to zero-crossing
  - False alarms and data dropouts due to speckle



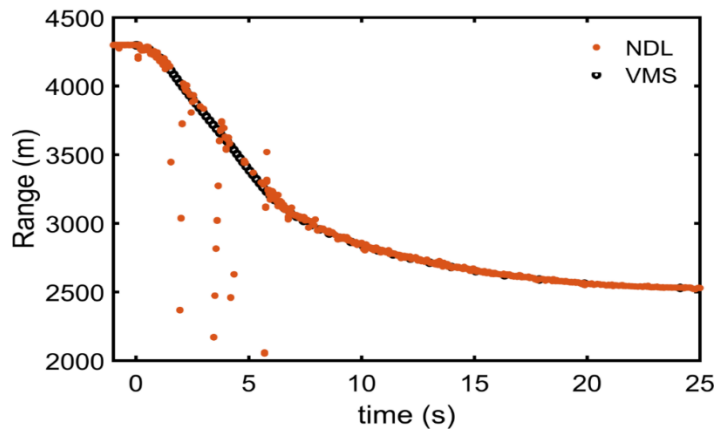
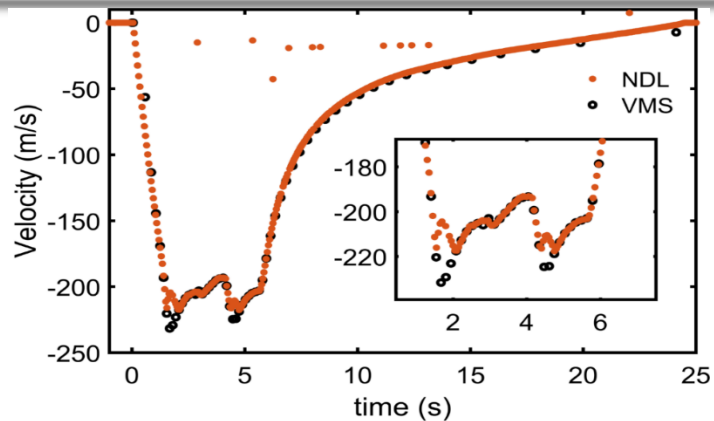
$$R = \left( \frac{TC}{2B} \right) \left( \frac{f_1 - f_2}{2} \right)$$

$$V = \left( \frac{\lambda}{2} \right) \left( \frac{f_1 + f_2}{2} \right)$$

$$V = \left( \frac{\lambda}{2} \right) (f_D)$$



# Rocket-Sled Test: Maximum Velocity Measurement



- Measured velocities to NDL limit of 218 m/sec at 4 km range

